VIBRATION ALGORITHM THRESHOLD ASSESSMENT ON TEST RIG AND FLIGHT DATA

FAA Rotorcraft Program Review
Health and Usage Monitoring System (HUMS)
February 13-15, 2007

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OUTLINE

- Technical Objectives
- Approach
- Details
- Budget
- Issues
- Research Accomplishments
- Planned Research

TECHNICAL OBJECTIVES

Develop a **process** for setting thresholds to identify the health of dynamic drive system components in a test rig that can be used to assess helicopter transmission health.

Compare the performance of gear vibration algorithms in a test rig to a helicopter transmission.

Define false alarm rates using the same threshold for both test rig and helicopter data.

Define thresholds for specific gear fault detection algorithms

APPROACH

Task 1: Provide an overview of current vibration methods used to identify the health of helicopter transmission gears.

Review published papers on conditions indicators (CI's) and health indicators (HI's) used in (HUMS) to detect gear damage.

Survey HUMS manufacturers on the methods used to identify drive train damage.

Review methods used to set thresholds to detect damage.

APPROACH

Task 2: Evaluate the effect of operational conditions on the three data sets (flight data, healthy test stand data, and faulted test stand data) and if CI data distributions change when damage occurs.

Flight Data

Review documents on the OH58 flight tests.

Summarize results of analysis performed on OH58 flight data.

Identify effects of accelerometers and maneuvers on CI's using statistical parameters.

Identify the CI data (sensor location, maneuver) that best represents the OH58 flight data using statistical analysis tools.

APPROACH

Task 2 (continued)

Test Stand Data

Document OH58 transmission test stand data available.

Summarize results of analysis performed on OH58 rig data.

Select data set for analysis.

Identify effects of accelerometers and operating conditions on CI's using statistical parameters.

Identify the CI data (sensor location, operating condition) that best represents the OH58 test stand data.

Flight and Test Stand Data

Compare CI data collected from OH58 helicopter with no damage and OH58 transmission test stand data with and without damage.

APPROACH

Task 3: Set standard thresholds CI's that correlates the performance of rig data to flight data for minimum false alarms or maximum sensitivity to damage.

Review CI algorithms that have performed well for specific faults.

Review health indicators (HI's) that provide decision making tools.

Apply threshold setting methods using statistical distributions, decision making tools and/or methods identified in review.

Assess the performance on OH58 helicopter data and test stand
Define the process required to apply this analysis to additional data.

APPROACH

Task 4: Develop a standard method to evaluate condition indicators developed in a test rig for application in a helicopter.

Define the steps in the process to perform the analysis on a different platform and/or fault.

Task 5: Provide the FAA with the required reporting requirements for this research.

The Principal Investigator will coordinate with the FAA on progress and direction of FAA requirements.

OH58 HELICOPTER FLIGHT DATA

Vibration data collected at NASA Ames from an OH-58 helicopter transmission.

Data collected from 14 different maneuvers.

Pilot set-up maneuver, then collected data for 34 seconds.

Data collected for 12 repetitions of each flight maneuver.

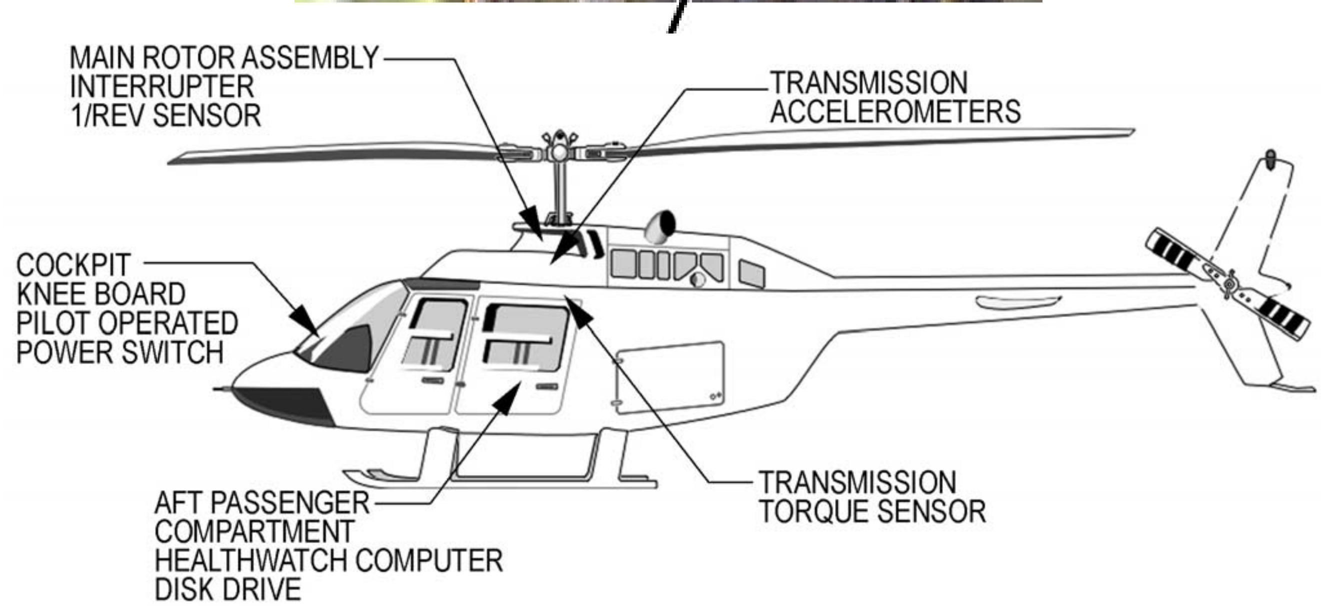
Data collected under steady flight conditions and low surface wind conditions (< 5 kt).

No mechanical component/transmission damage observed during flights.

OH58 HELICOPTER FLIGHT DATA

Manever	Torque	Maneuver Description
A	55%	Level, forward
B	80%	Level, forward
C	58%	Level, sideways left
D	58%	Level sideways right
E	55%	Climb,
F	15%	Descent
G	26%	Flat pitch on ground
H	74%	Hover, ~10 ft
I	74%	Hover~10 ft, turn left
J	73%	Hover~10 ft, turn right
K	61%	20^{o} bank left turn
L	61%	20^{o} bank right turn
M	80%	Climb
N	35%	Descent

OH-58 HELICOPTER



OH58 HELICOPTER FLIGHT DATA

Three vibration measurements (A1, A2, A3) are from single axis accelerometers (Endevco 7259A-10) mounted horiz/radial to the transmission.

Three vibration measurements (A4, A5, A6) are from a triaxial accelerometer (Endevco 7253A-10) with A4 mounted vertical, A5 horiz/axial and A6 horiz/radial to the transmission.

All accelerometers are attached to existing vertical studs surrounding the transmission housing using mounting brackets.

Engine torque and a once per revolution tachometer pulse from the rotor shaft is also collected.

OH58 HELICOPTER FLIGHT DATA

Vibration data sampling rate 50KHz(18KHz anti-aliasing filter)

For each 34-second maneuver, 48 time synchronous averages were calculated.

Main transmission - 19 tooth pinion on the output shaft of the engine meshes with a 71 tooth spiral bevel gear.

Sun gear of epicyclic gearbox on spiral bevel gear shaft – planet cage drives main rotor.

Turbine engine gearbox output - 50 tooth gear on pinion gear shaft.

The gear vibration algorithms focused on the health of the 19-tooth pinion on the input shaft of the main rotor transmission.

OH58 TRANSMISSION TEST STAND

Vibration data collected in NASA Glenn 500 HP Transmission Test Stand.

Torque and a once per revolution tachometer pulse from the rotor shaft is also collected.

Accelerometer installed on the helicopter housing.

Data collected at 100% speed, torque from 40 to 150%, mast loads from 0 to 100%.

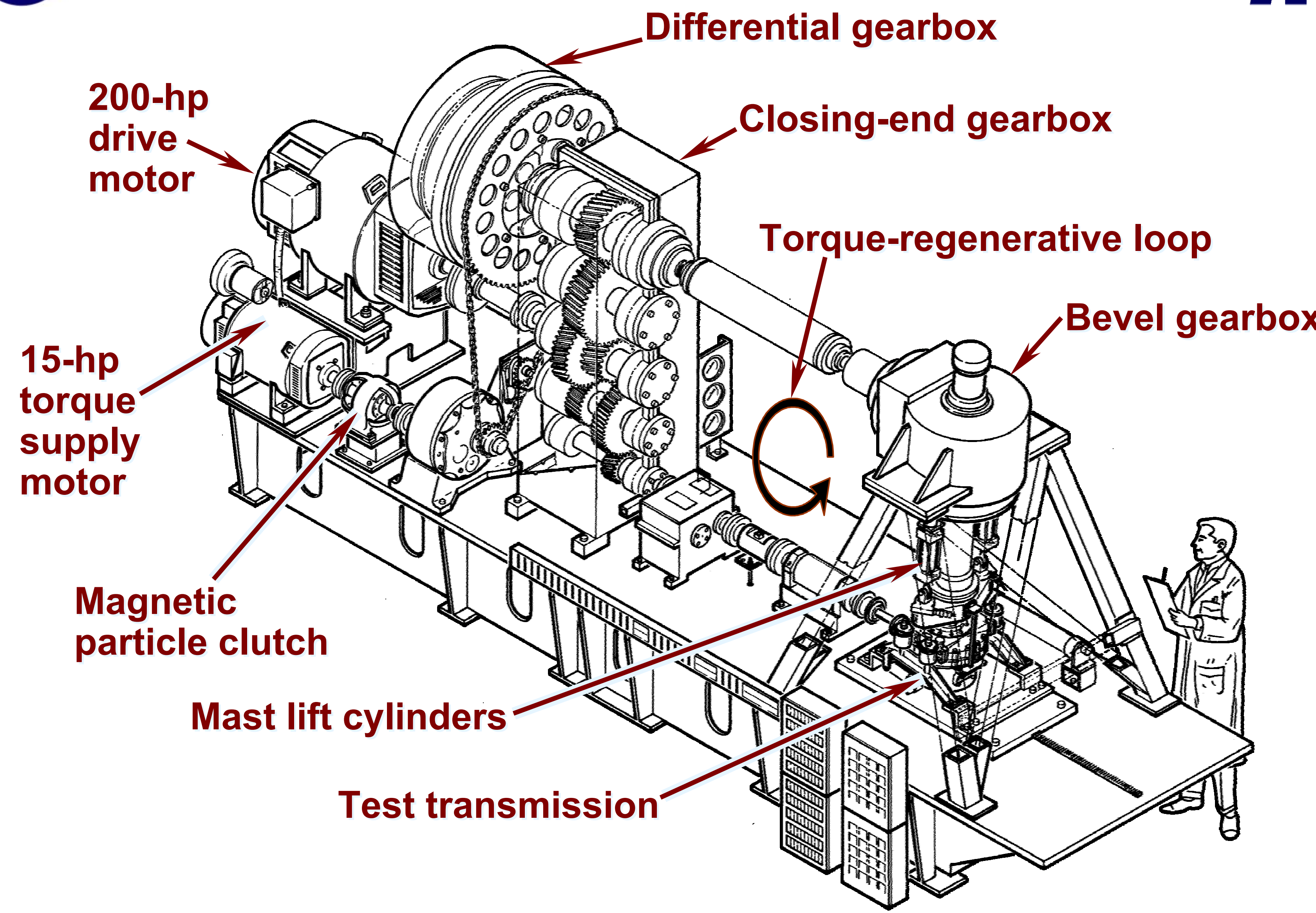
Vibration data sampling rate 150 KHz (55 KHz anti-aliasing filter).

Data collected during tests with and without damage.

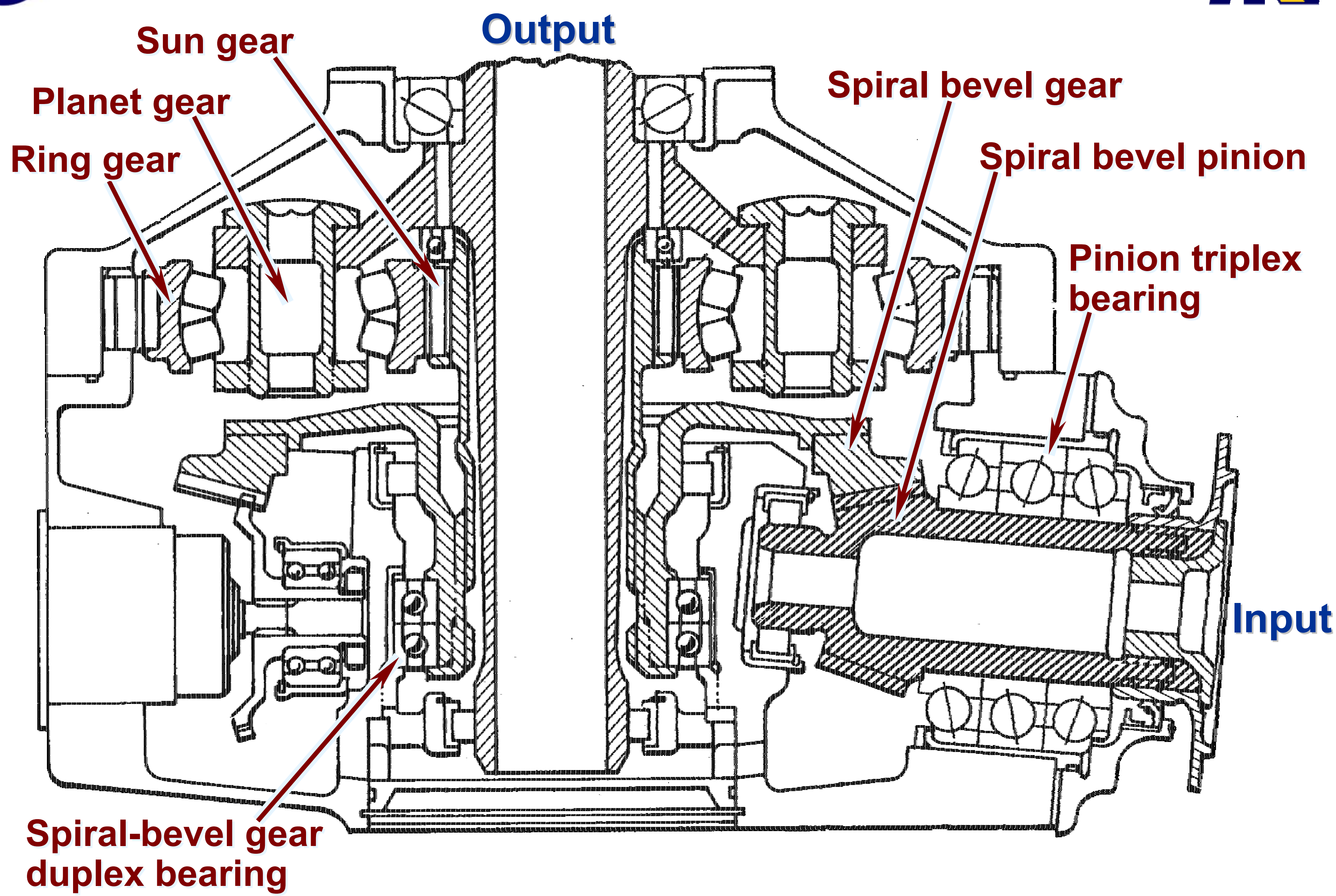
OH58 TEST STAND DATA

1	Sun gear tooth pit
2	Spiral bevel pinion heavy wear, scoring
3	Planet bearing IR spall
4	Top cover housing crack
5	Mast bearing micro-pitting
6	Planet bearing IR spall
7	Sun gear tooth pit
8	Sun gear tooth pit
9	Planet gear spall, small
10	Sun gear tooth pit
11	Planet bearing cage failure
12	Spiral bevel pinion tooth crack
13	Duplex bearing race spall
14	Triplex bearing race spall

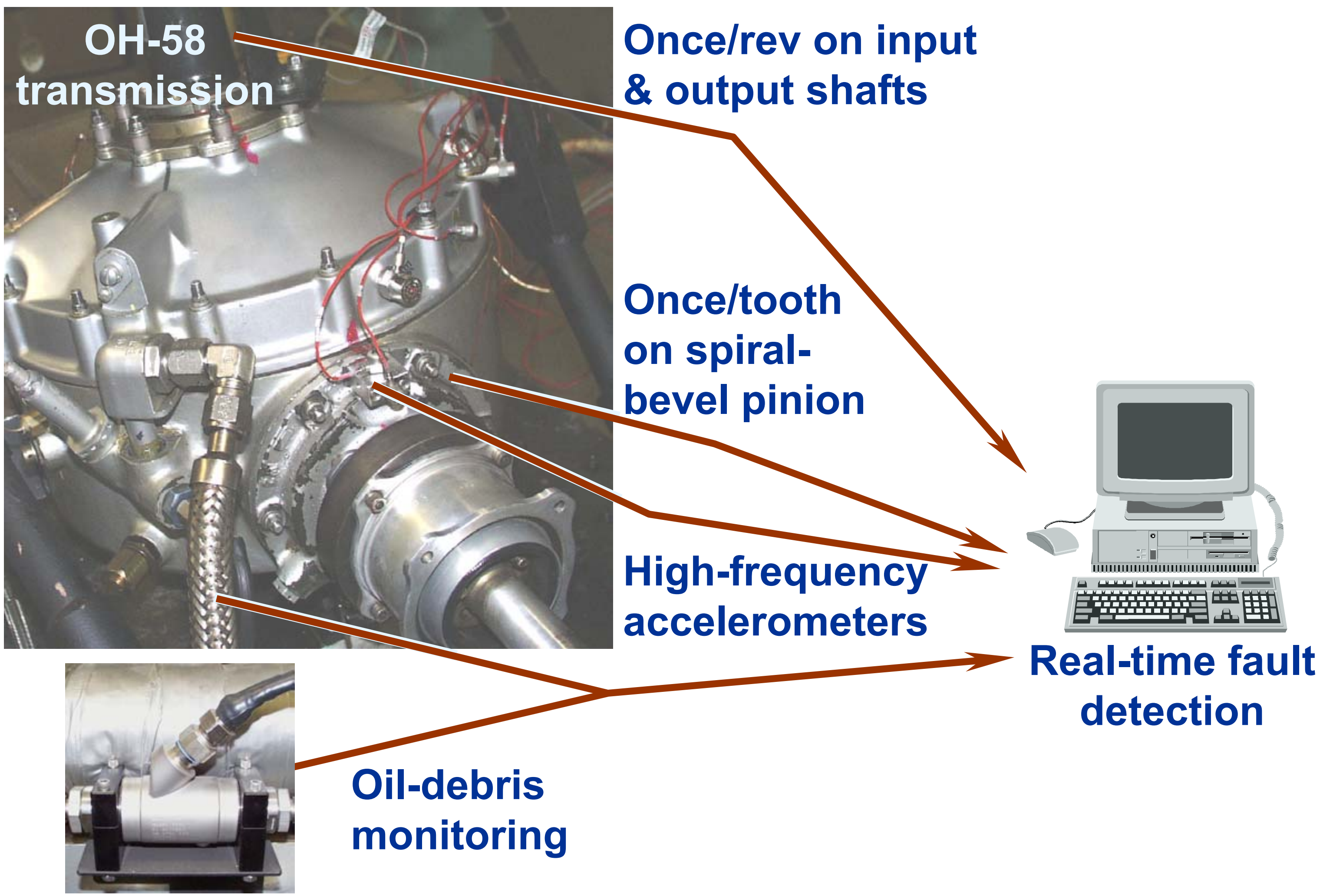
OH58 TRANSMISSION TEST STAND



OH58 TRANSMISSION TEST STAND



TEST INSTRUMENTATION



GEAR VIBRATION ALGORITHMS (CI's)

INPUT Sensor Data

Time synchronous averaged (TSA)vibration data

Fast Fourier Transform

Filter

FM4 - Gear Meshing Frequency Harmonics, 1st Order Sidebands

Inverse Fast Fourier Transform

Difference Signal(Filtered TSA) = d

$$\frac{\frac{1}{N}\sum_{n=1}^{N}\left(d_n-\overline{d}\right)^4}{\left[\frac{1}{N}\sum_{n=1}^{N}(d_n-\overline{d})^2\right]^2}$$

FM4

OUTPUT CI

SETTING THRESHOLD METHODS

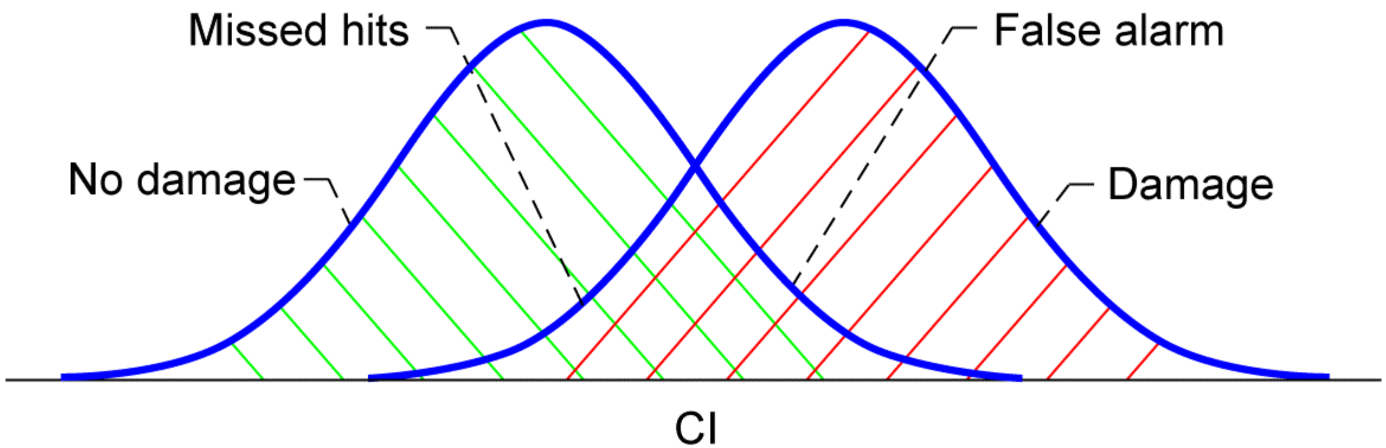
↑ Damage Detection Rates   ↓ False Alarm Rates

- Set simple limits on individual CI's ($\pm$ standard deviations).
- Set limits on combined (averaged, fused) CI's.
- Statistical methods - differentiate between damage and no damage condition from data distributions.
- Decision making tools - fault/no fault (hypothesis tests, Bayesian statistics, rule based systems, fuzzy logic).

SETTING THRESHOLDS

False Alarms versus Missed Hits

- Define threshold to maintain sensitivity to gear damage with minimal false alarms.
- Tradeoff between damage sensitivity and false alarms.



		No Gear Damage	Gear Damage
Decision	Indicate No Damage	Correct Decision	Missed Hit
	Indicate Damage	False Alarm	Correct Decision

FUZZY LOGIC

Sensors

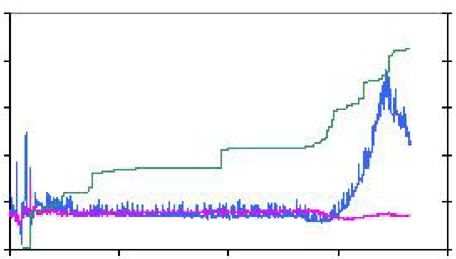
Accels

1X/Rev

Oil Debris

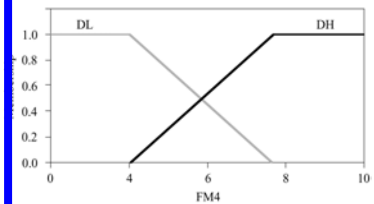
CI's –Inputs

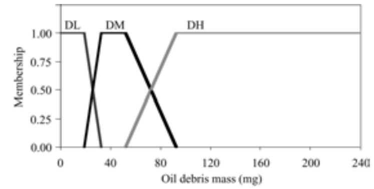
FM4, NA4, Debris

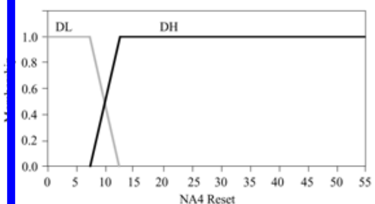


Fuzzy Logic/Data Fusion

Membership Functions



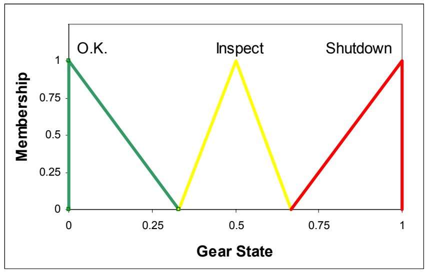




Rules

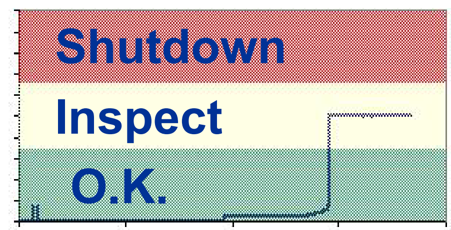
Damage Levels

Rule	FM4	NA4	Debris	Output
1	DL	DL	DL	O.K.
2	DH	DH	DH	Shutdown
3	DL	DL	DM	Inspect
4	DL	DH	DL	O.K.
5	DL	DL	DH	Inspect
6	DH	DL	DL	O.K.
7	DH	DL	DM	Inspect
8	DH	DH	DL	Inspect
9	DH	DL	DH	Shutdown
10	DH	DH	DM	Inspect
11	DL	DH	DH	Shutdown
12	DL	DH	DM	Inspect



Decision

Gear Health



BUDGET SUMMARY

Overall	Expenditures to Date
$220,000	$47,021

ISSUES

- Analysis of existing data collected in the OH58 Test Stand will only demonstrate the applicability of test rigs to qualify the performance of HUMS CI's in a flight environment for specific failures and components.

- Flight fault data is required to verify damage detection sensitivity demonstrated in test rigs can be maintained in a flight environment. The availability of this data is limited and currently does not exist in the NASA database.

- If additional failure data is required, additional work may have to be performed.

RESEARCH ACCOMPLISHMENTS

- Published the report, "Investigation of Current Methods to Identify Helicopter Gear Health." This report reviews techniques used to process (CI's), guidelines used by the FAA & CAA in developing and certifying (HUMS), CI's used in commercial HUMS, and different methods used to set thresholds.

- Reviewed OH58 flight tests documents to define the operational conditions, test set-up, data collection, and data analysis.

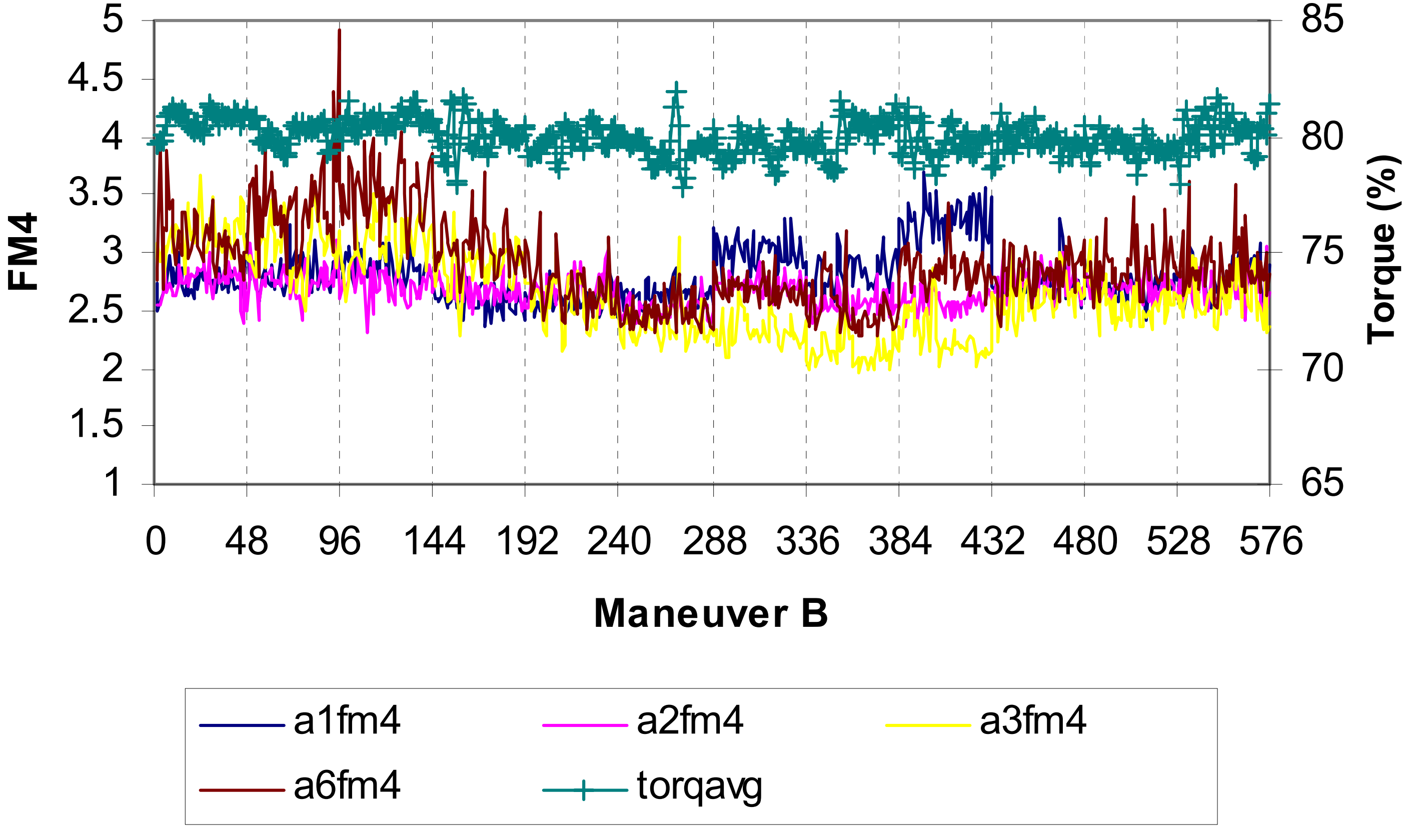
- Analyzed FM4 and RMS versus torque of 6 accelerometers for 14 flight maneuvers using statistical parameters.

RESEARCH ACCOMPLISHMENTS

- Calculated the probability of false alarm for the CI's of the two maneuvers performed during level flight.
- Plotted probability density function (PDF) plots of the flight CI's and rig CI with cracked tooth fault.
- Collected reference information from commercial HUMS manufacturers on CI's that have performed well for specific gear faults.

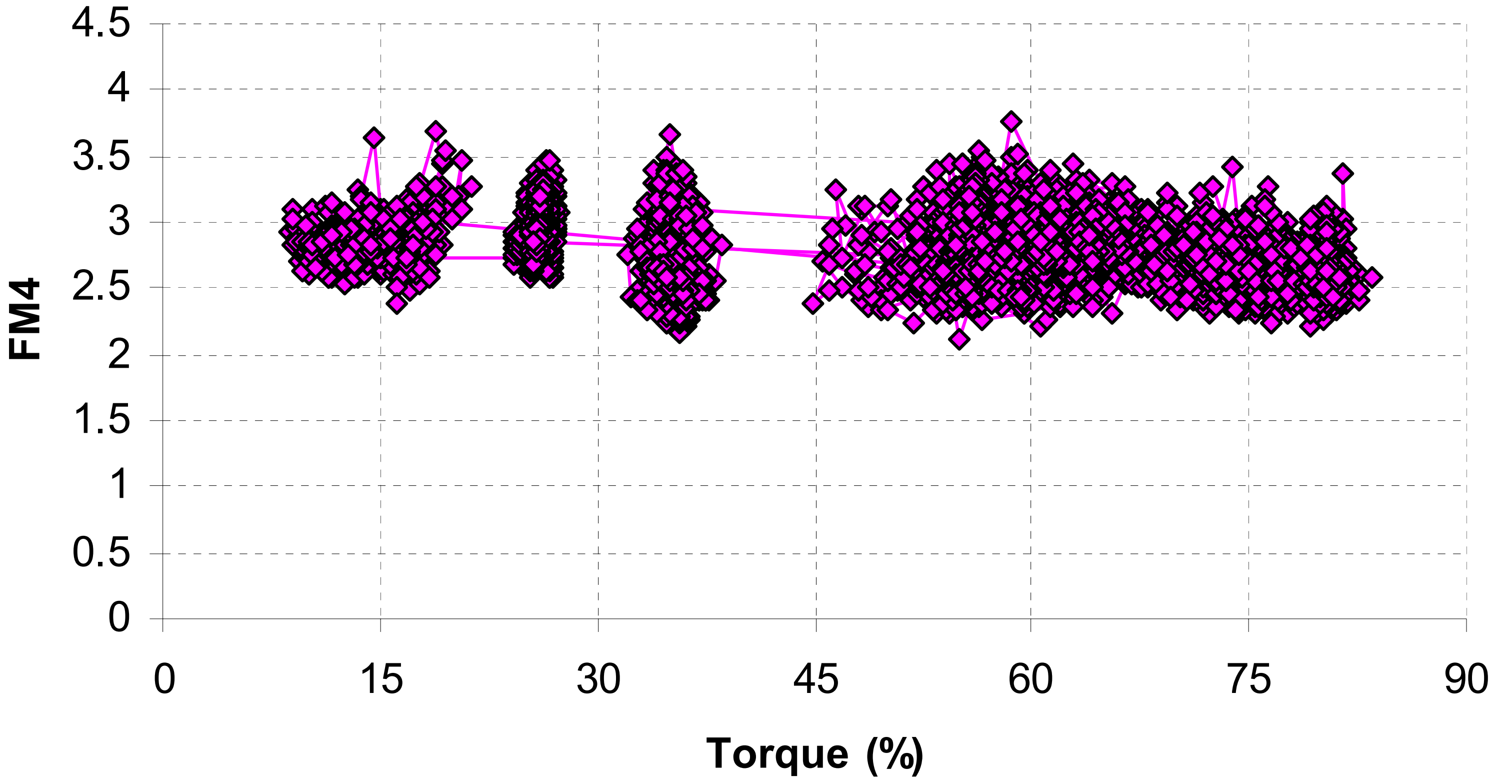
RESEARCH ACCOMPLISHMENTS

FM4 and RMS plotted for 6 accelerometers for 14 maneuvers. No trends observed between torque, accelerometer and maneuver.



RESEARCH ACCOMPLISHMENTS

FM4 and RMS plotted for 6 accelerometers versus torque. No simple relationship exists between gear CI and torque.



RESEARCH ACCOMPLISHMENTS

Detection Decision Matrix

Outcome	Fault	No Fault	Total
CI indicates Fault (D1)	a Number of detected faults	b Number of false alarms	a + b Total number of alarms
CI does not indicate fault (D0)	c Number of missed hits	d Number of correct rejections	c + d Total number of non-alarms
	a + c Total number of faults	b + d Total number of no faults	a + b + c + d Total number of cases

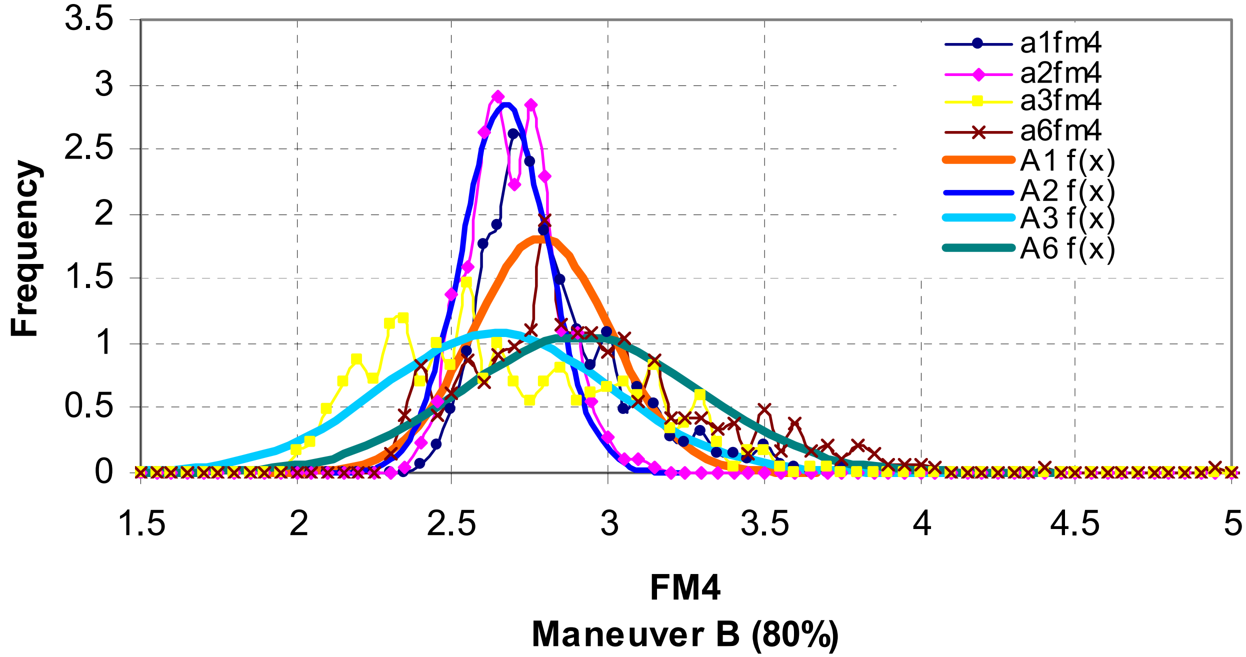
Probability of False Alarm Rate b/(b+d) for Maneuver B

FM4 Threshold	A1	A2	A3	A6
3	0.215	0.026	0.241	0.385
3.25	0.064	0	0.085	0.194
3.5	0.017	0	0.014	0.109
3.75	0.002	0	0.000	0.038
4	0.000	0	0.000	0.009

RESEARCH ACCOMPLISHMENTS

PDF of 4 accelerometers for Maneuver B and normal distribution based on mean and std. dev.

Min A1	**Min A2**	**Min A3**	**Min A6**
2.36	2.31	1.97	2.27
Max A1	**Max A2**	**Max A3**	**Max A6**
3.70	3.12	3.66	4.92
Mean A1	**Mean A2**	**Mean A3**	**Mean A6**
2.79	2.67	2.64	2.91
StDev A1	**StDev A2**	**StDev A3**	**StDev A6**
0.22	0.14	0.37	0.38



PLANNED RESEARCH

- Analyze healthy and faulted rig CI data at different torque levels. Calculate statistical parameters for healthy and faulted test stand data sets.
- Assess the performance (false alarms/missed hits) of threshold setting methods on OH58 helicopter data and OH58 transmission test stand data.
- Define the process required to apply this analysis to additional data.